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ACTIVE GRAVITY OFFLOADING SYSTEM WITH INFRARED TRACKING FOR ROVER TESTING

Travis Wavrunek
Michigan Technological University, tawavrun@mtu.edu

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By

Travis A. Wavrunek

A REPORT

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2021

This report has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

Department of Mechanical Engineering-Engineering Mechanics

Report Advisor:	*Paul van Susante*
Committee Member:	*Gordon Parker*
Committee Member:	*Jung Yun Bae*
Department Chair:	*William W. Predebon*

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Author Contribution Statement

Thank you to Elijah Cobb who designed developed the ground control software used in MK2 and MK3 as well as providing insights on developing a more effective tracking software.

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Thanks to Dr. Paul van Susante guidance and advice throughout the development of the gravity offloading system and to the PSTDL for providing the funding and facilities for this project. Thank you to Dr. Gordon Parker and Dr. Jung Yun Bae for acting as committee members and providing feedback though the defense process. Additionally, thank you to Dr. William Reid from JPL for his feedback on the initial system design and insights into rover tracking.

List of Abbreviations

ARGOS	Active Response Gravity Offload System
DOF	Degree of Freedom
FPV	First-Person View
GO	Gravity Offloading
IR	Infrared
IRGO	Infrared Gravity Offloading
JSC	Johnson Space Center
PSTDL	Planetary Surface Technology Development Lab
POGO	Partial Gravity Simulator
TCP	Transmission Control Protocol
WAGM	Walking Anti-Gravity Machine

Abstract

Gravity offloading is a tool used to test how different gravitational forces will impact the mobility of rovers bound for Lunar or Martian expeditions. Previous approaches have been successful in simulating partial gravity environments, and this report details how the Infrared- Gravity offload (IRGO) system, developed for the Planetary Surface Technology Development Laboratory (PSTDL) and lunar simulant sandbox, has a similar aim. Through a series of iterations, IRGO has been developed to actively track an infrared beacon and follow a rover within the test chamber to eliminate inertial and friction forces along two horizonal axes. A portion of a rover’s weight is offloaded using a passive counterweight system to provide a third translational degree of freedom. Future plans to incorporate a lightweight gimbal as well as an active vertical axis are also discussed as solutions to improving the IRGO system.

1 Introduction

As development of extraplanetary vehicles progresses, so does the need for simulating the effect that gravitational forces will have on them. Gravity offloading devices can help address this need by providing a test environment where rovers can be verified with partial gravity conditions to simulate how mobility factors may be impacted. Gravity offloading devices achieve this by reducing the forces between the vehicle and ground using a variety of techniques.

The gravity offloading system described in this report was designed specifically for the Planetary Surface Technology Development Laboratory (PSTDL) at Michigan Technological University. However, conclusions drawn and techniques developed from this testing can be applied to a range of similar gravity compensation systems.

1.1 System Requirements

The PSTDL requested that the gravity offloading system function with various rovers in an array of testing conditions. This variety required that the offloading system provide a variable offloading force with minimal modification to the system. Further, the system was anticipated to be used in slope testing, requiring that it be capable of vertical motion up to 1.5 meters and facilitate 3-axes of rotation to accommodate rover traversal over obstacles. Additionally, the system was expected to operate in a harsh environment of abrasive regolith dust and in complete darkness to simulate the conditions of a lunar permanently shadowed region.

1.2 Related Systems

There have been many different approaches to simulate the effects of reduced gravity on both rovers and astronauts, with varying degrees of application. Freefall methods, such as parabolic flights, provide the greatest simulation of reduced gravity and full DOF, however the limited test volume, short testing duration (40-60 tests of 25 seconds), and high cost restrict the amount of data that can be collected [1]. Buoyancy methods such as helium balloons have also been used. However, these methods are limited to the amount of weight they can offload and are not ideal for dynamic movements due to large resistances from air drag. [2] Mechanical methods such as cranes and pulley carts are more versatile in comparison because they are not restricted to scale or speed and are therefore common for developments requiring long periods of testing. This method was chosen to fulfil the PSTDL's needs, primarily due to the lab space and the amount of testing that a permanent installation allowed. Additionally, this approach will allow for reduced expenses over time and works well for a range of rover sizes. Mechanical methods can be separated into two design types. Passive mechanical designs still face the issue of adding friction and mass to the system. Active systems mitigate this by actively positioning the offloading system above the mounting points of the rover. However, such positioning systems require accurate tracking to maintain tension in the offloading line.

Current mechanical approaches balance their limitations through innovations in design and scope. The following section provides an overview of two comparable published active systems and analyzes the benefits and restrictions of each design in consideration of the PSTDL's needs.

1.2.1 ARGOS

Johnson Space Center's Active Response Gravity Offloading System (ARGOS) is a large profile gravity offloading system able to accurately offload up to 750 lbs of gravitational force to simulate microgravity conditions. The design, shown in Figure 1.1, is similar to an overhead bridge crane with a 41'x41'x25' profile. ARGOS functions as an offloading system for human and robotic payloads and is commonly used to support a variety of different applications, including robotic development and design evaluations.

Figure 1.1 JSC ARGOS During Human Mobility Testing [3]

ARGOS can offload its payload vertically by using an electric motor with an inline load cell to control the tension of the cable. The vertical motor offloads payload weight at a speed of 10 ft/s for 300 lb payloads and 4 ft/s for 750 lb payloads. Movement along the horizontal axes also relies on electric motors. Friction drive wheels move each horizontal axis so that it can respond to horizontal traversal at a speed of 10 ft/s, independent of payload's weight [3].

JSC's system can react quickly to any changes in horizontal movement by measuring the angle of displacement of the tension cable. This measured angle is processed by the control loop, keeping the offloading trolley directly above the moving payload.

ARGOS is one of the most versatile and established gravity offloading systems. The relatively low mass of the offloading trolley allows for quick movements and the crane-like structure allows for a large test area while maintaining a sizable max payload.

1.2.2 WAGM

The Walking Anti-Gravity Machine is a system developed by CSA engineering to simulate microgravity conditions for spacecraft mechanisms such as solar arrays with low inertial forces. The WAGM system was designed have minimal friction, a semiportable setup, and a minimal impact on its test environment. The main design feature of the WAGM system, shown in Figure 1.2, is the vertical offloading stage powered by a pressure-regulated air spring. The air spring provides up to 160 lbs of offloading force within ± 0.008 lbs. Further, with the assistance of a pulley system, WAGM is capable of 72” of vertical payload movement. [4]

The horizontal travel of the system is relayed by two linear belt-driven tracking stages. Tracking is done using a similar angle-sensing mechanism to ARGOS. The tip-tilt sensors shown in the figure measure the angle of displacement using accelerometers oriented normal to the guide tube. As the guide tube pivots on a universal joint, the accelerometers send displacement data to the control system which positions WAGM over the payload. Horizontal travel speed was not a design criterion for the system as the max payload speed was tested at 0.15 in/second.

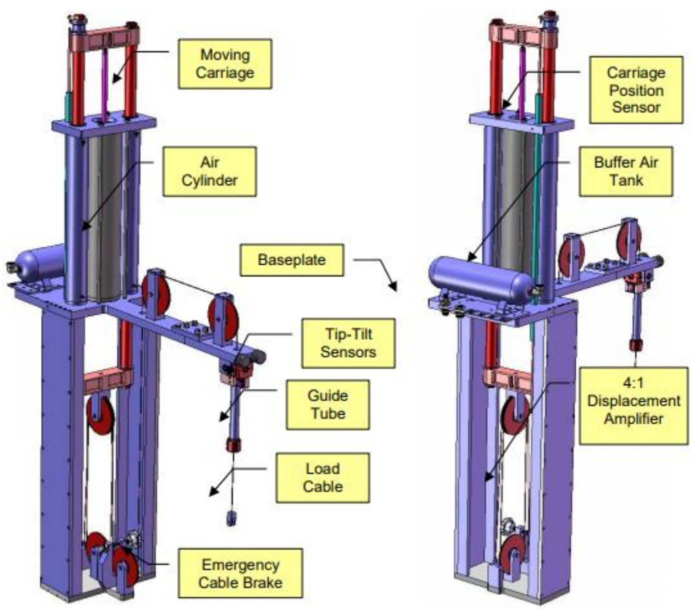

Figure 1.2 WAGM System Detail Overview

WAGM is a very accurate approach to gravity offloading that allows for low drag forces in the vertical direction and a very accurate offloading force. However, the air cylinder and pulley configuration fill a large profile and have not been tested on systems requiring faster movement.

2 Mechanical and Electrical Design

2.1 Test Space

The PSTDL lunar simulant sandbox is a 6’x20’x9’ vinyl enclosed chamber with a 6’x6’ chamber serving as an airlock between the lab space and the sandbox. The remaining 14’ of the enclosure serves as the test area. Within the test area, a regolith bed contains 3800kg of lunar simulant filled to a depth of 30 cm for terrain testing of lunar rovers. Additionally, an optional variable angle ramp can be installed for slope testing. Figure 2.1 shows a representation of facility.

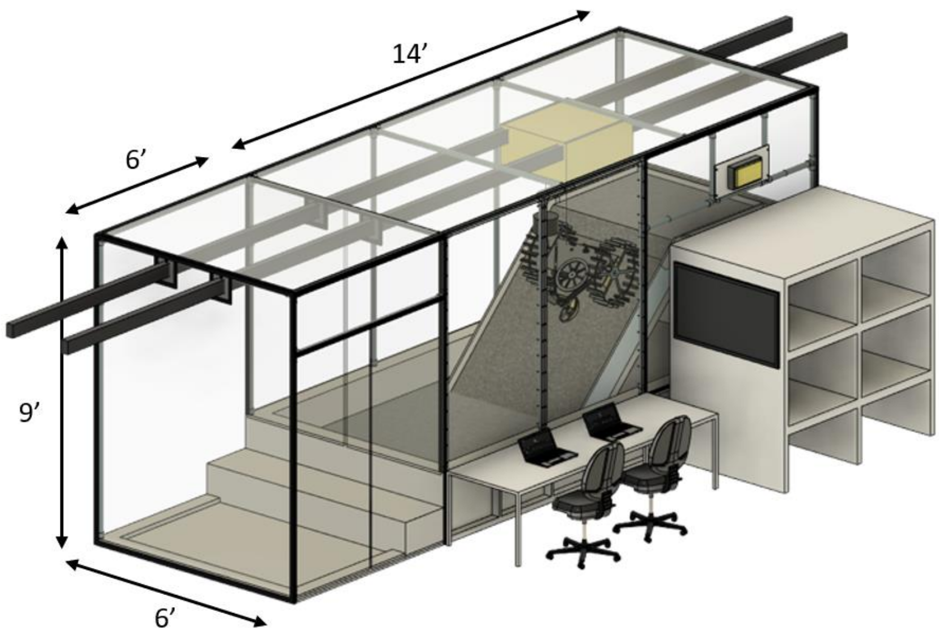

Figure 2.1 Render of Simulant Sandbox in the PSTDL

The rail track above the sandbox testbed predated the PSTDL and simulant sandbox. This track came equipped with an existing metal cart sized for the rail. The track is ceiling mounted with a weight rating of 250 lb and spans the entire length of the lab.

2.2 Design Considerations

An active mechanical gravity offloading system was chosen for the IRGO because of its reduction in excess inertial forces and frictions compared to passive system designs. Passive gravity offload systems are reliant on the payload to pull them along, creating a horizontal component to the offload force. Active systems avoid this issue by tracking the payload to move the trolley directly above the rover, reducing horizontal forces. The tradeoff here is that active systems introduce more complexity and if done incorrectly, can cause inaccuracies in positioning.

The simulant within the PSTDL sandbox is MTU-LHT-1A lunar simulant and is easily made airborne during testing causing a constant layering of dust to cover every surface within the test chamber. Worries of dust coating wheels and causing slipping or dust buildup on the outside of the wheels motivated the decision to use a belt design rather than a friction wheels like ARGOS. For the short axis (referred to as the X-axis and shown in Figure 2.2), self-lubricating sleeve bearings were chosen over a roller-wheel track because of weight savings and robust mounting design. The T-slot frame with sleeve bearings was found to be lighter than an equivalent roller-wheel track.

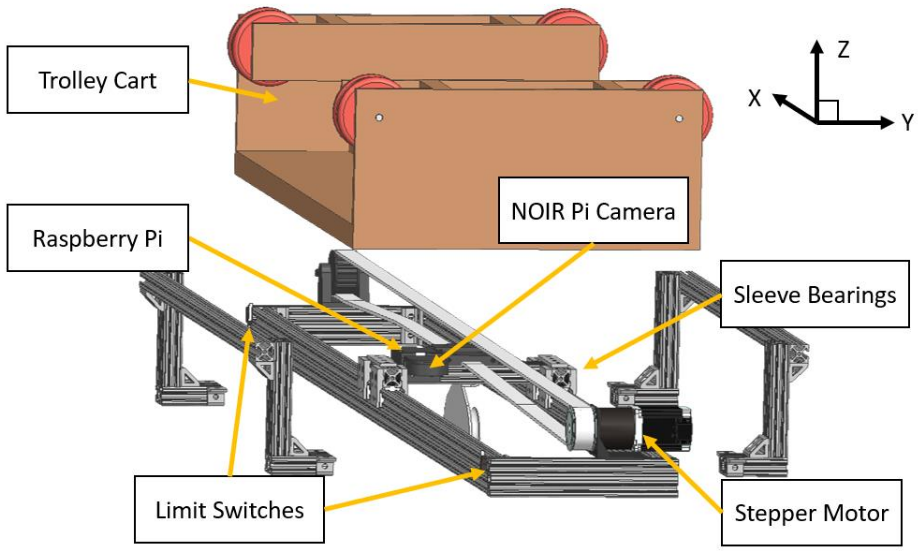

Figure 2.2 Exploded View of Gravity Offloading Trolley

Stepper motors were chosen to drive the belts over brushless DC motors. Both motor options would work well for the application, but stepper motors were chosen because of their precision in tracking location. This was more important in the MK1 version described in section 4.1, where manual control of the trolley's location was the only mode of command.

Three choices of technologies for tracking a rover were identified – AprilTags, IR tracking, and cable angle displacement. AprilTags were considered but rejected due to the need for a large tag that would be unsuitable for smaller rovers. Concerns of settled simulant obscuring the tag and the lack of light within the test chamber were also considered. IR tracking and cable angle displacement were both considered viable solutions for handling the dusty and dark environment for rovers of nearly any size.

However, IR tracking was chosen rather than the angle displacement method due to the sealed enclosure of the IR camera being more compact and less susceptible to damage from the abrasive simulant. Additionally, a system not reliant on contact with the tension cable is desired because the IRGO system will be used with a variety of different tension lines dependent on rover weight.

2.2.1 Mechanical Design

The PSTDL gravity offloading system is a two-axis belt driven system shown in Figure 2.3. The X-axis is built from a T-slot frame and suspended from the Y-trolley which moves along the Y-axis. The stepper motors move the horizontal axes of the system using an abrasion resistant polyurethane belt with Kevlar reinforcement to position itself directly above any spot within the sandbox. The low-resistance vertical axis pulleys are mounted on the x-axis trolley and support the tension need for gravity offloading.

Figure 2.3 Photo of PSTDL IRGO Trolley

In order for the offloading force to be applied realistically to the rover, the rover must be able to rotate freely about its center of gravity. To accomplish this a gimbal mounting platform is used. The gimbal acts as an interface between the rover and tension cable to translate the offloading force of IRGO system through the center of gravity, allowing for rotation. It is crucial that the forces exerted on the rover move through the center of gravity, otherwise these forces will impact the rotation of the rover in unintended ways. As a part of the mechanical design of the system, a two-axis gimbal was developed for the T-REX [5] rover, shown in Figure 2.4. This system allowed the rover to tilt along the lateral direction and turn about the vertical axis.

Figure 2.4 Gimbal with Two Axes of Rotation

Drawbacks from the two-axis gimbal were observed during obstacle testing with the T-Rex rover, Figure 2.5. As the wheels of the rover moved over an obstacle, the front skid lifted into the air because the rover had no way to pitch along its longitudinal axis. Solutions have since been developed to overcome this issue, and future gimbal design strategies are discussed in section 4.2.

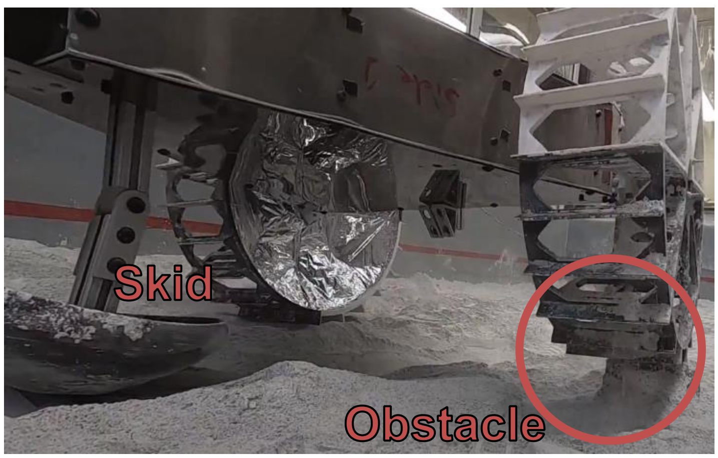

Figure 2.5 Gimbal Testing with Two-Axis Gimbal

2.2.2 Infrared Tracking

In order to isolate the IR beacon on the rover, an IR filter and digital camera were used along with image post-processing using OpenCV. A high pass IR filter, used occasionally in photography or for security monitoring, was chosen as it allows higher wavelengths within the IR spectrum to pass while blocking any wavelengths below the specified threshold. A high-wavelength beacon and filter are useful in isolating the IR beacon source, as they reduce interference created by reflections or other light sources. Figure 2.6 shows a comparison between two IR filters taking a photo of a 950 nm IRLED. The 950 nm filter blocks background objects while allowing the high wavelength light to pass through to the camera. Although the filter is unable to prevent all lens flair, post processing is used to fully isolate the source.

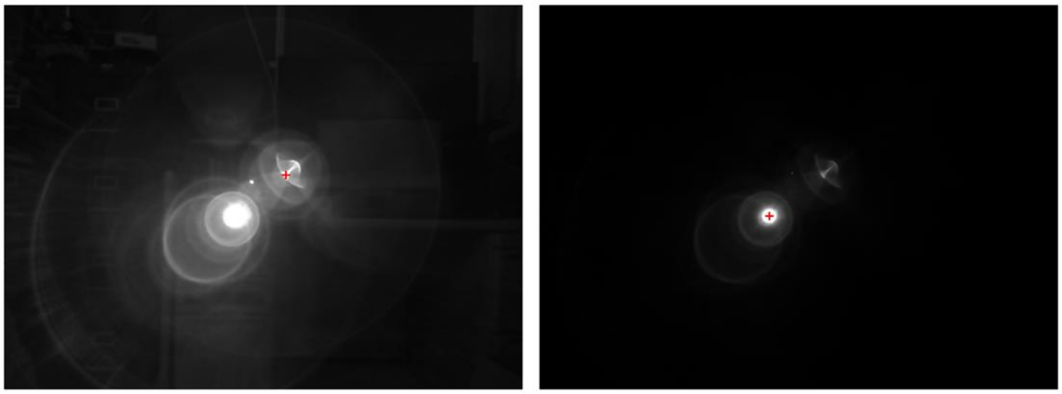

Figure 2.6 Photos IRLED Through Lens Filters of 720nm (left) and 950 nm (right)

Most digital cameras use a silicon-based sensor that is sensitive into the near-infrared region. However, IR-blocking filters are usually applied to these cameras to isolate images captured to the visible light spectrum. To take photos within the IR-A range, a non-blocking IR camera such as the PINoIR camera module is used.

Image processing is used to take the filtered image from the PINoIR camera module and find the center of the IR beacon. This process uses OpenCV, (code in 6A), an open-source computer vison software and is outlined in Figure 2.7. [6] The first step puts a greyscale image of the IR beacon through a command to set any pixels with a luminosity under a set threshold to black, and any pixels above the threshold to white. The IR filter makes this step effective at isolating the beacon. A binary-opening process is then used reduce noise in the image by removing any errant pixels smaller a set disk size within the image. Once the image is clean and binary, the image moments are calculated and used to find the centroid of the object. This centroid location is compared to a desired center point, a pixel representing the location of the trolley where offloading force is vertical, and results in the displacement value. This displacement value is used to calculate motor direction and speed used to track the rover.

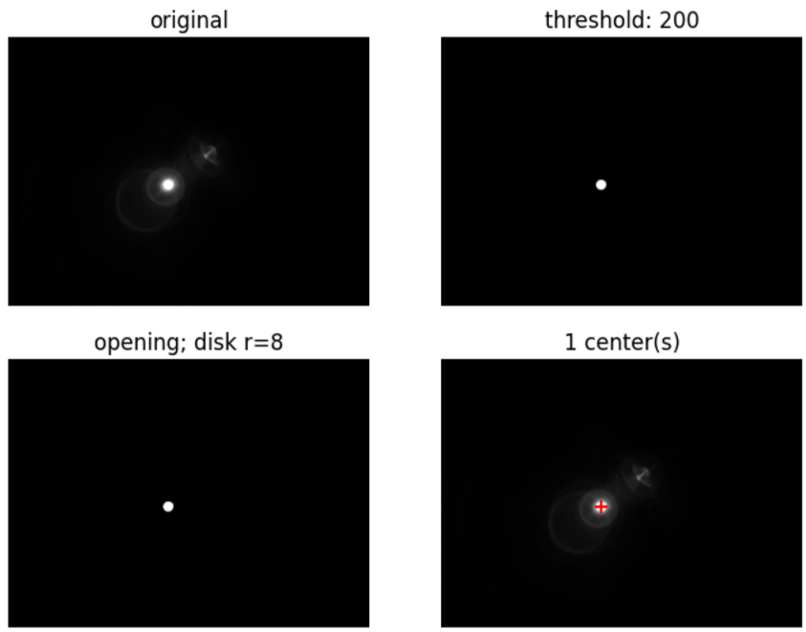

Figure 2.7 Image Processing Stages

To determine stationary accuracy and characterize noise, displacement data was collected with a stationary IR beacon. Figure 2.8 shows outputted data from a previous python NumPy version of the image tracking, which had a slower sampling rate than the C++ OpenCV version. Max error with the image tracking was recorded to be approximately .3 pixels. By passing this displacement data through a .5 Hz low-pass filter, error is reduced to less than .12 pixels. At the base of the lunar simulant sandbox, a pixel represents 2.6 mm. Using the low-pass filter, IRGO is able to locate the center of the beacon to with an error of .3 mm. The error can be reduced even further by increasing sampling rates.

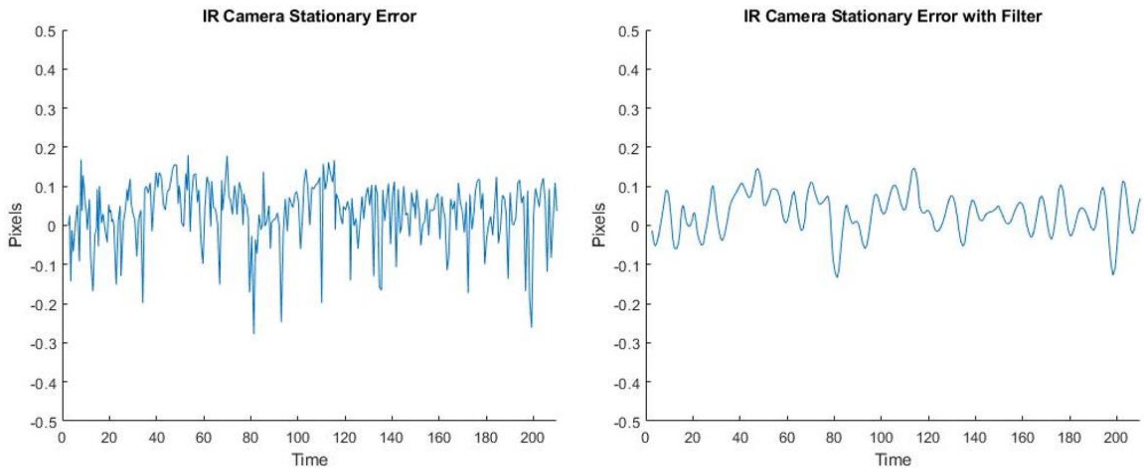

Figure 2.8 Displacement Data of Stationary Beacon with .5 Hz Low-Pass filter

3 Gravity Offloading Controller

3.1 MK1

The initial version of the gravity offloading system (Figure 3.1) was a manual control only system. Two separate Arduinos were connected to a laptop outside the enclosure over serial connection to a python program. A python program ran acted as ground control and required the user to input an axis and location within the chamber for the trolley to move to by using input commands in terminal window. The program would interpret these commands and send them over serial protocol to Arduinos which recorded the system's current location and interfaced with the motor controllers. An FPV camera was connected to a screen outside the chamber so that a user could see above the rover and position the trolley roughly above the center of gravity.

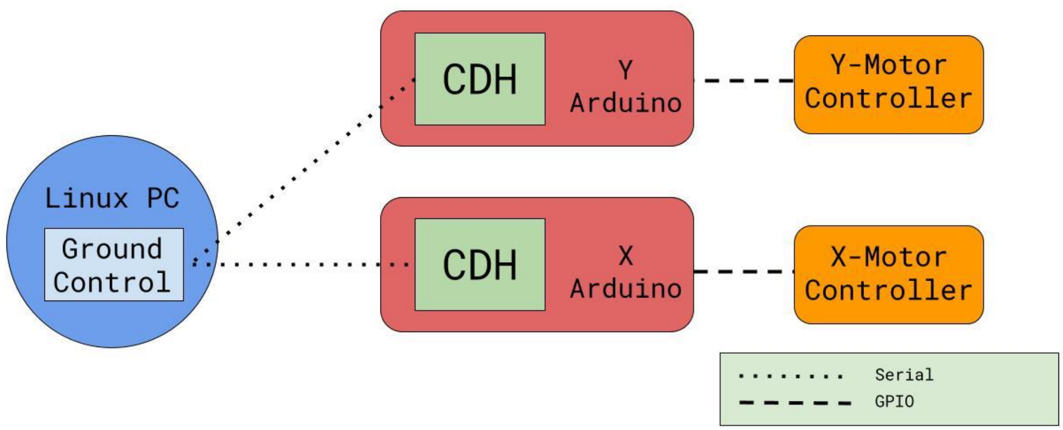

Figure 3.1 MK1 System Diagram

This system had multiple drawbacks that required further development. The ground control system was slow and relying on user estimation of the rover position to track the rover. The user had to constantly input new goal locations to keep up with the rover, which frequently led to the gravity offloading trolley falling behind or moving ahead of the rover. Inaccuracies in positioning caused horizontal forces on the rover which created a non-representative environment.

3.2 MK2

The second version of the gravity offloading system (Figure 3.2) added a Raspberry Pi Model 4 mounted outside the enclosure to interface with the Arduinos. This Pi was controlled over ethernet and communicated with a separate ground control software on a Linux machine. The ground control software controlled the gravity offloading system using directional keys and modifiable step values. While the system kept previous manual capabilities, IR tracking also began in this iteration using the camera from a Wii remote to track an IR beacon. The camera could recognize the location of the IRLED and report a relative location based on the camera's internal coordinates. This position was relayed over an I2C bus interfacing with an Arduino and then sent to the PI to be processed.

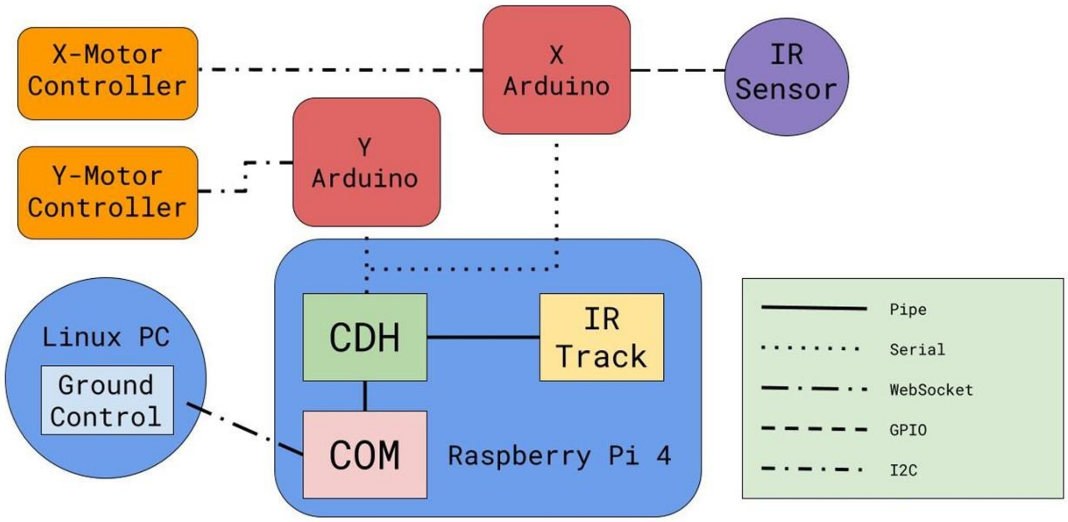

Figure 3.2 MK2 System Diagram

Transitioning to the Raspberry Pi and adding the control overlay simplified how the system was interfaced with by the user. However, the IR tracking system encountered difficulties with effectively managing the serial buffer between the Pi and the Arduino. Additionally, the Arduino was tasked with reading IR data, reading location commands, remembering position, interfacing with stepper motor drivers, and sending IR and position data to the Pi. Further development of the system to offload more processing onto the Pi could have improved functionality, general inconsistencies with how the MK1 code and MK2 code interfaced led to an early end for MK2 in favor of transitioning into a MK3 with a centralized controller and a higher resolution IR sensor.

3.3 MK3 – Current Iteration

The current iteration of the IRGO system (Figure 3.3) consists of the Raspberry Pi mounted on the x-trolley and is connected to a PC outside the chamber through an ethernet connection. The Pi software is written in a common systems programming language of C++ and manages the activities of the motors and IR tracking. Motors are controlled using the Pi’s I/O pins to provide digital signals representing motor direction and step speed. A TCP connection is used over ethernet to interface with the ground control software to interface with the entire system.

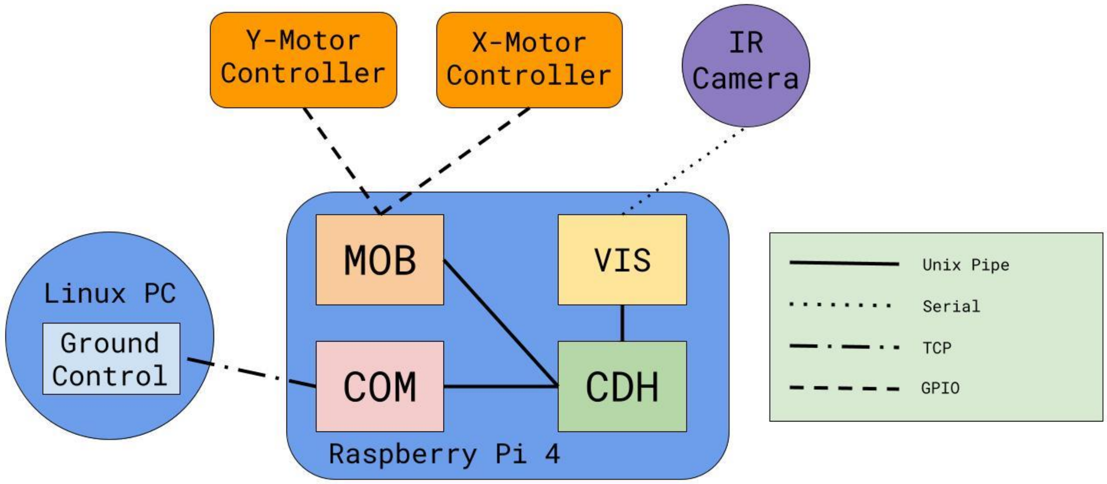

Figure 3.3 MK3 System Diagram

The IRGO system can be controlled in two different modes by the ground control software. The manual mode allows the system to be controlled via issuing velocity commands to each axis. IR mode uses the IR process described in section 2.2.2. The switch to controlling velocities instead of positions, allows for a system that can be more reactive to its environment.

3.3.1 Process

On startup, the Pi starts the control software that creates a TCP server and initializes the motor controllers. On receiving commands from the ground control instance, the process then propagates commands throughout the system's multiple threads. Each thread is responsible for committing actions. There is a thread for capturing images, processing images, communicating with the ground control instance, motor controllers, and a main thread to handle all children threads.

The ground control software is written in TypeScript, a superset of JavaScript and runs in the NodeJS runtime using the V8 JavaScript engine (Figure 3.4). The software is split up into two main processes. One being an ElectronJS process which provides native system interfaces, and the second being a process running ReactJS code for displaying and interacting with the user.

Figure 3.4 NodeJS Ground Control Software Interface

3.3.2 Impressions

Aspects of the MK3 version of the system are under development but what is done is promising. The centralized controller has allowed for a more coherent control structure where information can be passed simply between sub-systems.

IR tracking with OpenCV is has shown to be faster than the MK2 sensor with a higher resolution in data collection and larger field of view. With centralizing all process on the Pi, data collection and photo processing can happen independently on different threads, without causing holds on the entire system. The Pi camera also allows for more control over how the image is taken and provides more avenues for debugging. OpenCV allows for more versatility in how the beacon is differentiated from its environment.

Overall MK3 is a stable setup giving control to a centralized controller that will allow for future iterations to be built without having to deal with artifacts of past versions.

4 Future Work

Working from the stable foundation laid by MK3, future work will focus on improving the capabilities of the gravity offloading system. These improvements are centered on three focus areas:

- Implement a control system to enable tracking
- Develop a three-axis gimbal to provide realistic rotation
- Incorporate an active Z-axis to allow for dynamic rover movement

4.1 Improved Controls

The current control system of the IRGO system is undeveloped and mostly untested. The system uses a proportional control loop to determine the speed and direction of trolley’s movement based off the displacement value calculated by the IR tracker. Sampling rates with the Arduino-based system were less than 1 Hz, causing jerky and oscillating responses leading to an unstable system. The Pi-based system has a response rate greater than 5 Hz. Increasing image processing speeds by reading directly from the camera stream and removing read/write processes will increase processing speed and increase response rate. The implementation of a PID controller will reduce steady state error and allow for less oscillation.

A successful future control system will have an accuracy of within 1% of the total offloading force. For the PSTDL’s T-REX rover, weighing nearly 30 kg [5], error up to 10mm of deviation in any direction would be allowable. Lighter rovers will require a more stable system with less error and oscillation.

4.2 Gimbal Design

Accurate gimbal design is vital for conveying offloading forces to the rover. The current gimbal design is limited to rotation about two axes, providing better representation than a fixed mount, but still inaccurate for most mobility testing involving slopes or obstacles. A more advanced gimbal design, able to provide realistic rotation around the center of mass, must be developed.

Gimbals that are able to represent full 3-axis rotation have been developed for use with human mobility testing. These gimbals can be large and heavy, creating additional inertial moments of rotations and artificial resistance to movement when at rest. A gimbal developed for human mobility testing on the POGO system (Figure 4.1), a precursor to ARGOS, weighs 40 Kg and was reported to have a large negative impact on both static and dynamic tasks because of its large moments of inertia. [1]

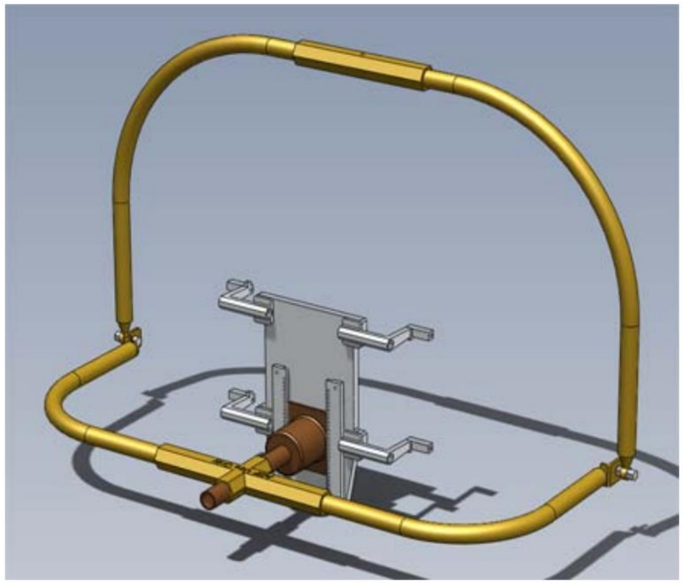

Figure 4.1 Human Mobility Testing Gimbal Used with POGO [1]

JSC developed two gimbals, the lighter of which is shown in Figure 4.2, as of the successors to the POGO system’s gimbal. The mass of the system was decreased to 24 Kg, and additional mounting versatility was added. The mass reduction between JSC’s two gimbals was noted as an improvement to gravity offloading quality [7]. A similar design will likely be developed for use withing the PSTDL sandbox.

Figure 4.2 ARGOS 3-Axis Gimbal Design [7]

4.3 Active Z-Axis

Currently the GO System uses the passive counter-weight system to offload gravity from a rover. This system is simple and effective at providing the desired counterforce and allows for vertical movements such as incline testing and obstacle traversal. However, the counterweight system has drawbacks when compared to an active system such as a load cell and motor or air cylinder.

The counterweight design is functional but undesirable, adding significant mass to the system as it must be the offloaded both the mass of the rover and any additional mass added by the gimbal to simulate lunar gravity. This added mass reduces the max rover weight that the system can support. Additionally, the counterweight mass creates an artificial inertial force in the vertical direction. Fast moving rovers will have difficulty testing with the counterweight method as quick movements in any direction will cause the weight to lag or pull the moving rover. The impact of this issue will likely increase as the weight of rovers decrease because of low inertial resistance of a low-weight rover. The mass hanging directly above the rover is also an undesired configuration. Though it is unlikely that the counterweight would fall, the consequences would be severe.

An active system allows for better dynamic movements in the vertical direction because of the removal of added inertial components. Additionally, the offloading force can be recorded from the inline load cell or pressure gauge to analyze the accuracy of the offloading.

5 Conclusion

Overall, the development of the PSTDL's IRGO system has made significant progress in providing a representative simulation environment for rover testing. Additional development of the systems capabilities will be carried out to further understand how the effects of gravity impact rover mobility to achieve the fidelity required to provide data representative of environmental testing.

Key results show that the IRGO system is able to function in the test environment of simulant sandbox and able to provide a variable offloading force throughout the test bed enclosure. Additionally, a tracking system has been developed that can follow an IR beacon and rover. Development of the system will continue to develop MK3 and beyond to integrate improved control logic, a representative gimbal, and an active Z-axis.

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A OpenCv Image Processing Code

```
/*
Name: Track_IRGO.cpp
Purpose: Finds center of IR light
Author: Travis Wavrunek
Contact: tawavrun@mtu.edu
Created: 3/16/2021
*/
#include<iostream>
#include <opencv2/core.hpp>
#include <opencv2/imgcodecs.hpp>

using namespace cv
mat sourceim, threshim, openedim;

int main()
{
    int threshlimit = 160;
    int elementsize = 5;

// read Image
    std:string impath = samples::findFile("IRPhoto");
    sourceim = imread(impath,IMREAD_GRAYSCALE);

//thresholding
    threshold(sourceim, threshim, threshlimt, 255, THRESH_BINARY);

//noise reduction, may want to remove to reduce time
    mat circle = getStructuringElement(MORPH_ELLIPSE,elementsize);
    morphologyEx(threshim, openedim, MORPH_OPEN);

//centriod
    Moments m= moments(threshim, true);
    Point center= Point (m.m10/m.m00, m.m01/m.m00)

    return center;
}
```